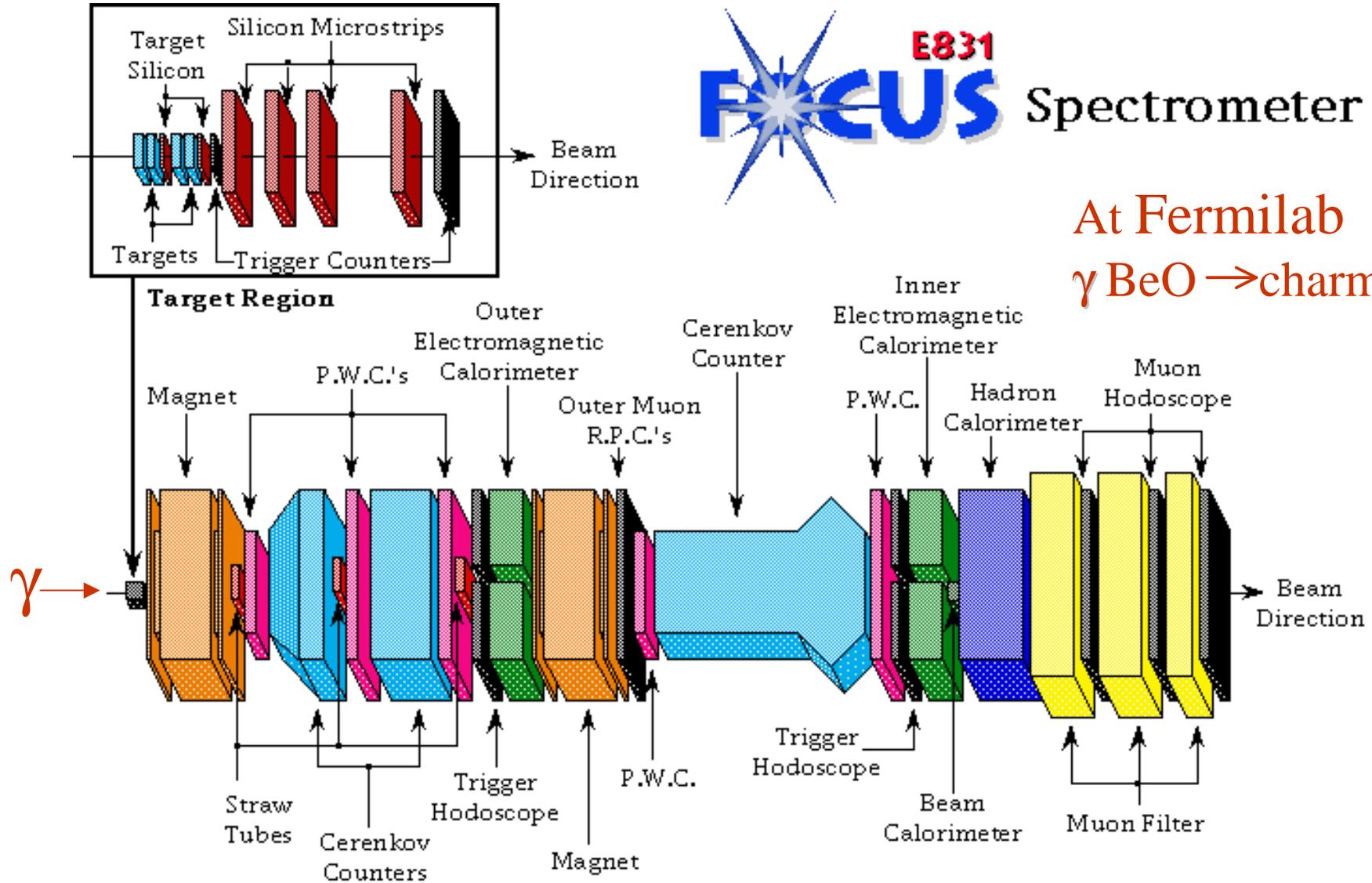


Charmed Hadron Spectroscopy At



Robert K. Kutschke
Fermilab
FCP01 March 7, 2001

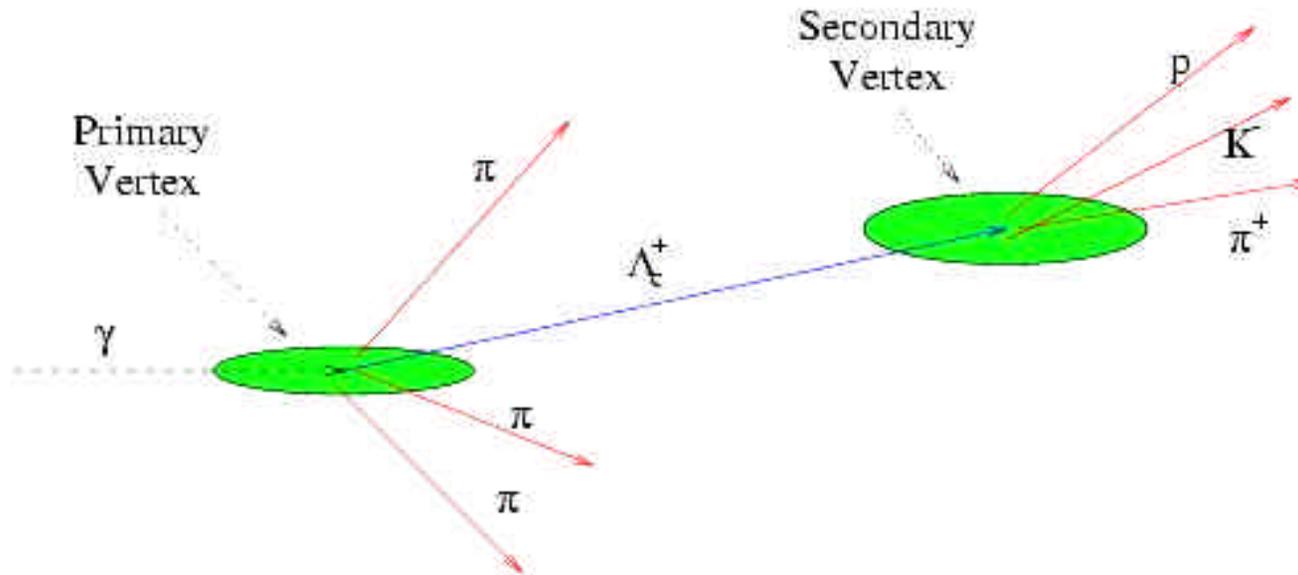
1. Introduction
2. D^{**}
3. D_S^{**}
4. Σ_C, Σ_C^*
5. Λ_C^*



FOCUS: The Successor to E687

- Segmented BeO Target interleaved with SMDs.
- Upgraded:
 - EM Calorimetry.
 - Cerenkov system.
 - Muon ID capability.
- Data taken in 1996-1997.
- More than 10 times the Luminosity
 - $>10^6$ reconstructed “Golden Mode” Decays:
 $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^- \pi^+$ and $D^+ \rightarrow K^- \pi^+ \pi^+$.

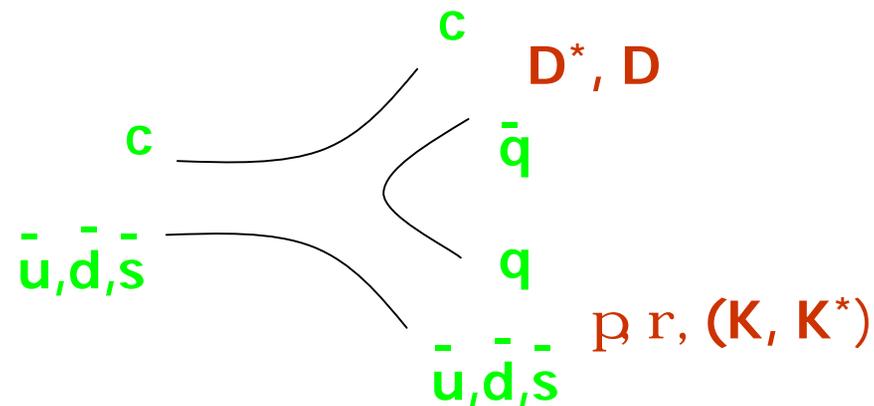
Candidate Driven Vertexing



- Find charm candidate: good vertex, good particle ID.
- Seed primary vertex finder with the charm candidate.
- Require isolated secondary. One measure: $L/\sigma_L > \text{cut}$.
- Add tracks from primary to form $\Lambda_c \pi$ combinations.

P-wave Charmed Mesons

- $L=1$ between c and light quark ($q=u,d,s$).
- $J_{\text{light}} = S_{\text{light}} + L$, approximately good Q number if $m_c \gg \Lambda_{\text{QCD}}$
Rosner: "the hydrogen atom of QCD"
- Idealized picture is a "doublet of doublets".
- Strong decays to $D^{(*)}\pi$ (or $D^{(*)}K$ for D_s)



Idealized Picture of P-wave Charmed Mesons



Heavy quark symmetry:

$j_l=3/2$ dominant decays are D-wave

$j_l=1/2$ dominant decays are S-wave

Reminder:

$$D: J^P = 0^-$$

$$D^*: J^P = 1^-$$

$$J_{\text{light}}^P = 1/2^-$$

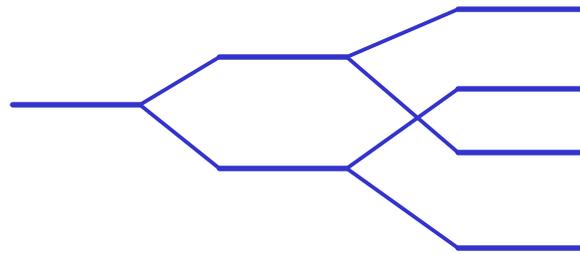
Angular Momentum and Parity Selection Rules

Decay	L	Decay	L	
$2^+ \rightarrow 1^- 0^-$	2			
$\rightarrow 0^- 0^-$	2			
		$3/2^+ \rightarrow 1/2^- 0^-$	2	$1^+_{3/2}$ Decays via D-wave
$1^+ \rightarrow 1^- 0^-$	0, 2			$1^+_{1/2}$ Decays via S-wave
$0^- 0^-$				
		$1/2^+ \rightarrow 1/2^- 0^-$	0	
$0^+ \rightarrow 1^- 0^-$				
$0^- 0^-$	0			

All 5 decays in the multiplet are described by 2 parameters, the **S** wave and **D** wave amplitudes (x Wigner 6-j, x phase space)

What's Overly Simplified in the Ideal Picture?

- Doublets may overlap (which 1^+ is more massive?)

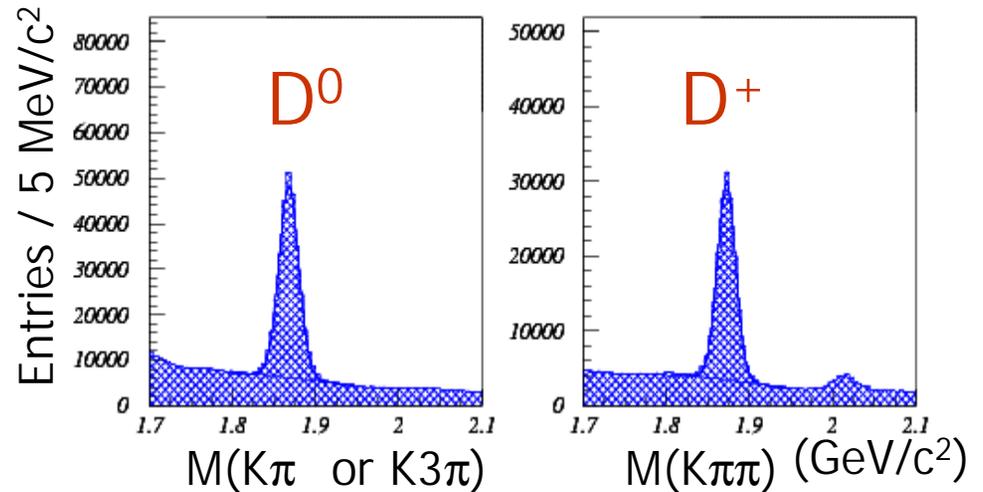


- Is suppression of S wave widths complete?
- D_{s1} right at threshold for D^*K :
 - Very narrow, $\Gamma < 2.3 \text{ MeV}/c^2$ @ 90% CL.
 - Data suggests mostly S-wave!

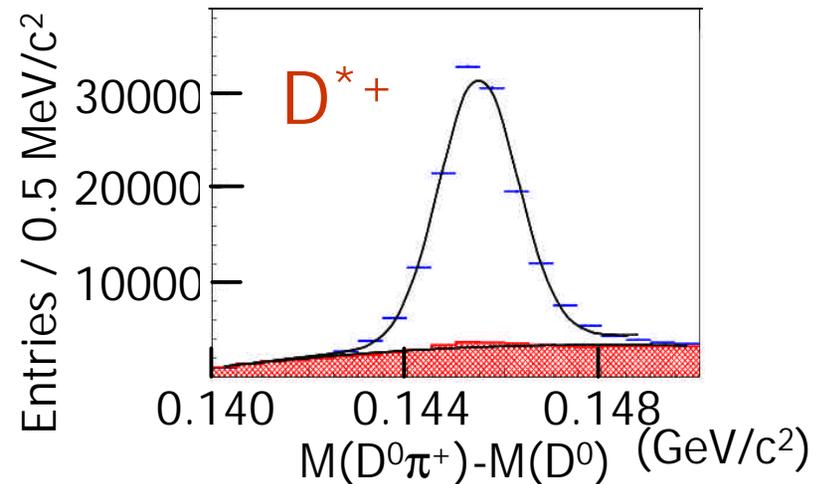
S-Wave Charm States at FOCUS



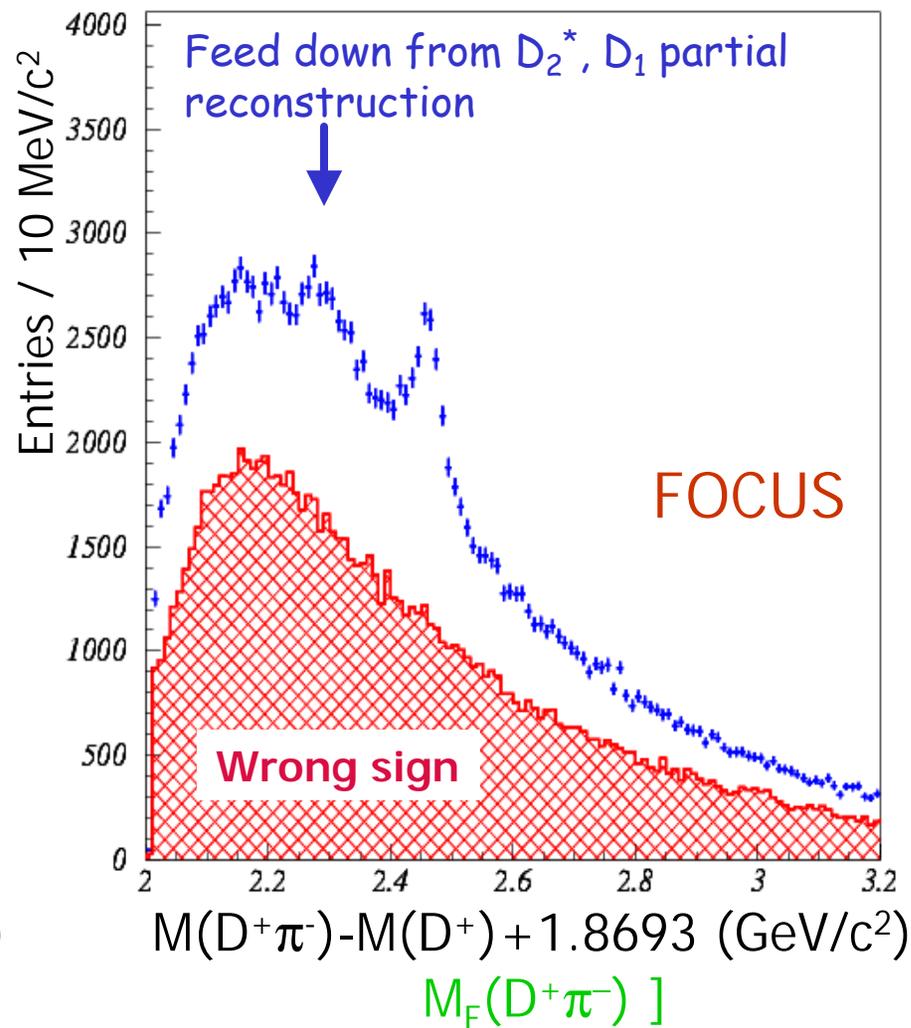
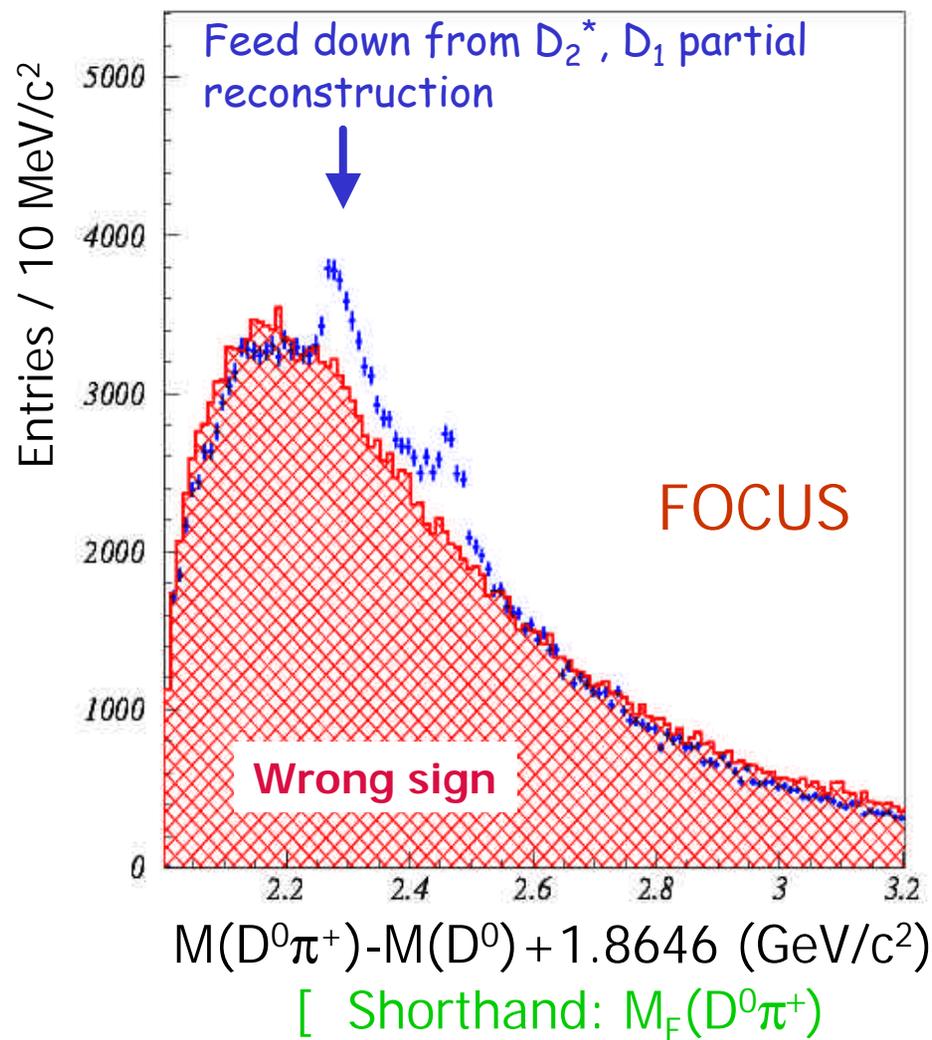
For $S/B > 7$,
 $> 330,000$ D candidates



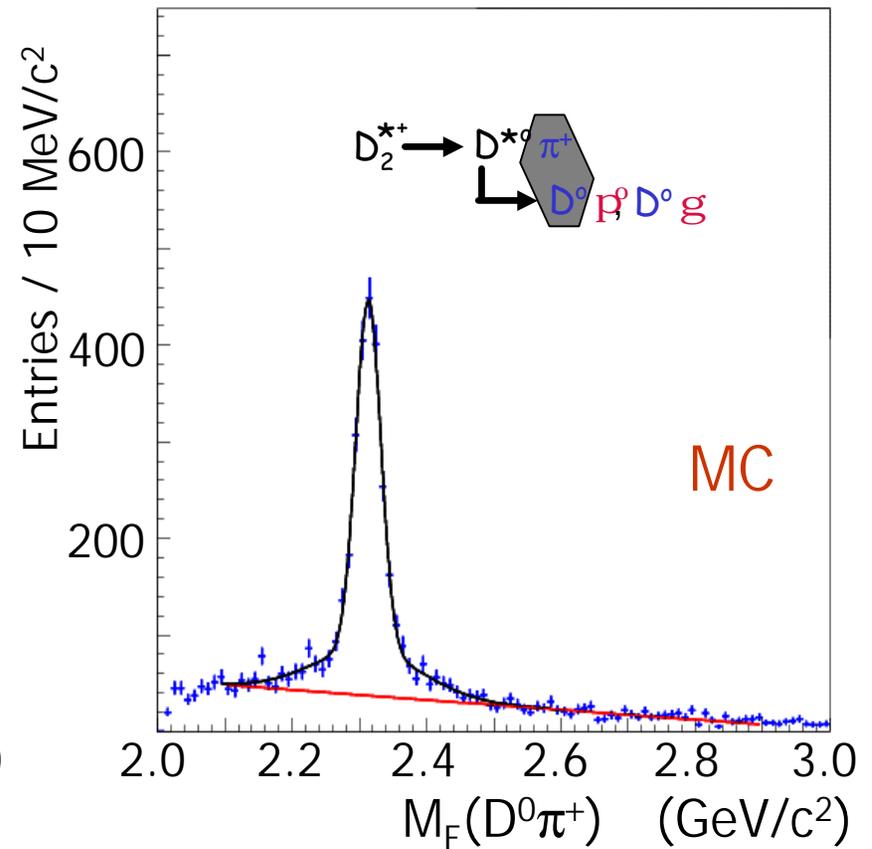
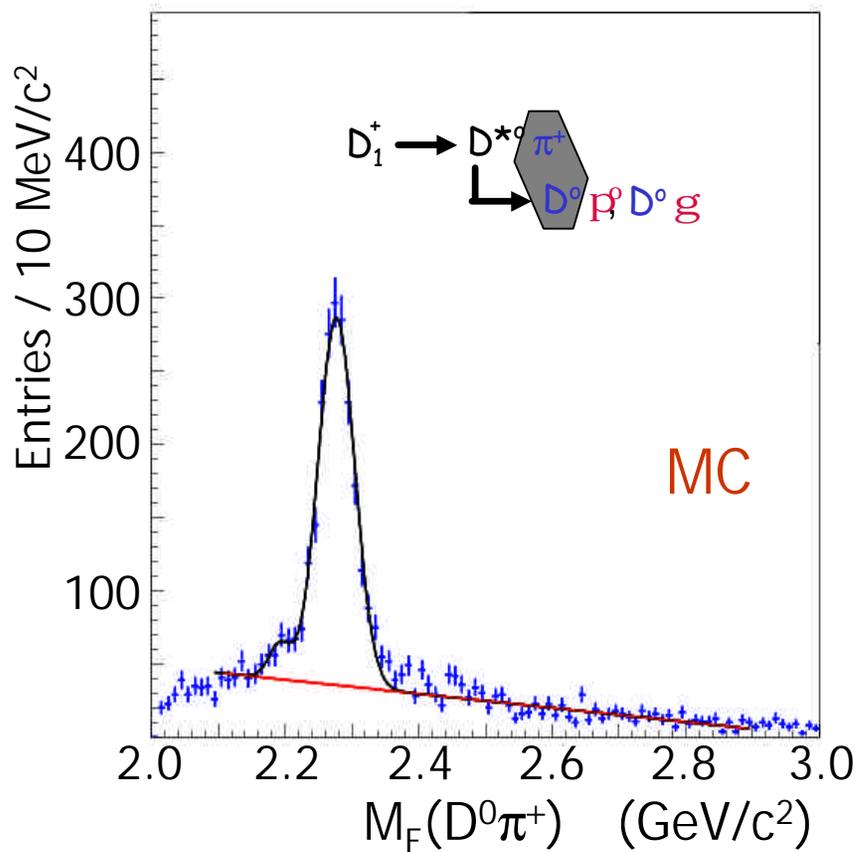
For $S/B > 5$,
 $\approx 70,000$ D^{*+} candidates



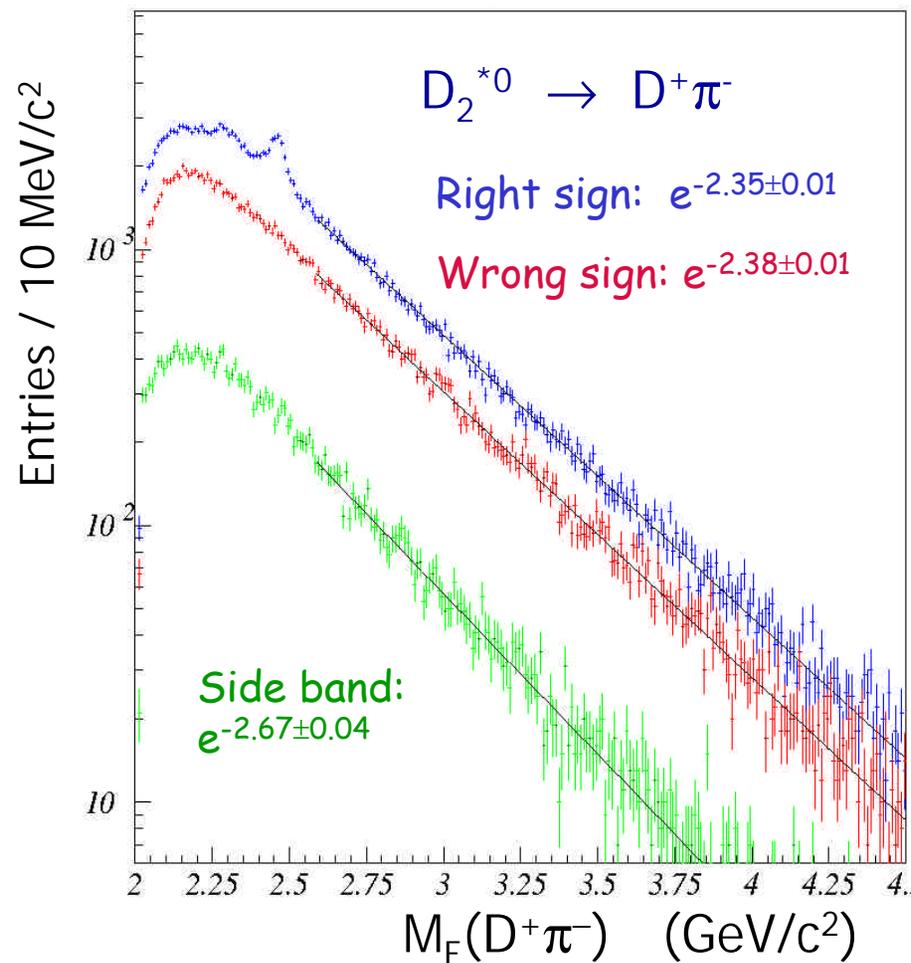
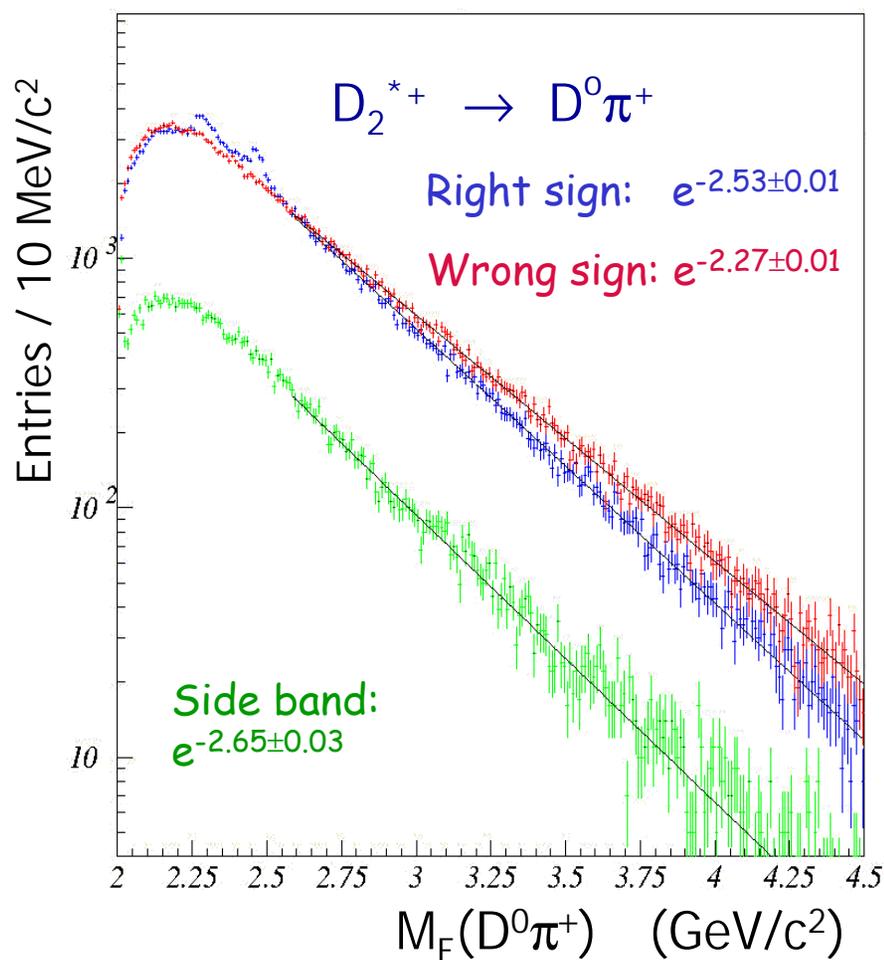
$D^0\pi^+$ and $D^+\pi^-$ Mass Distributions



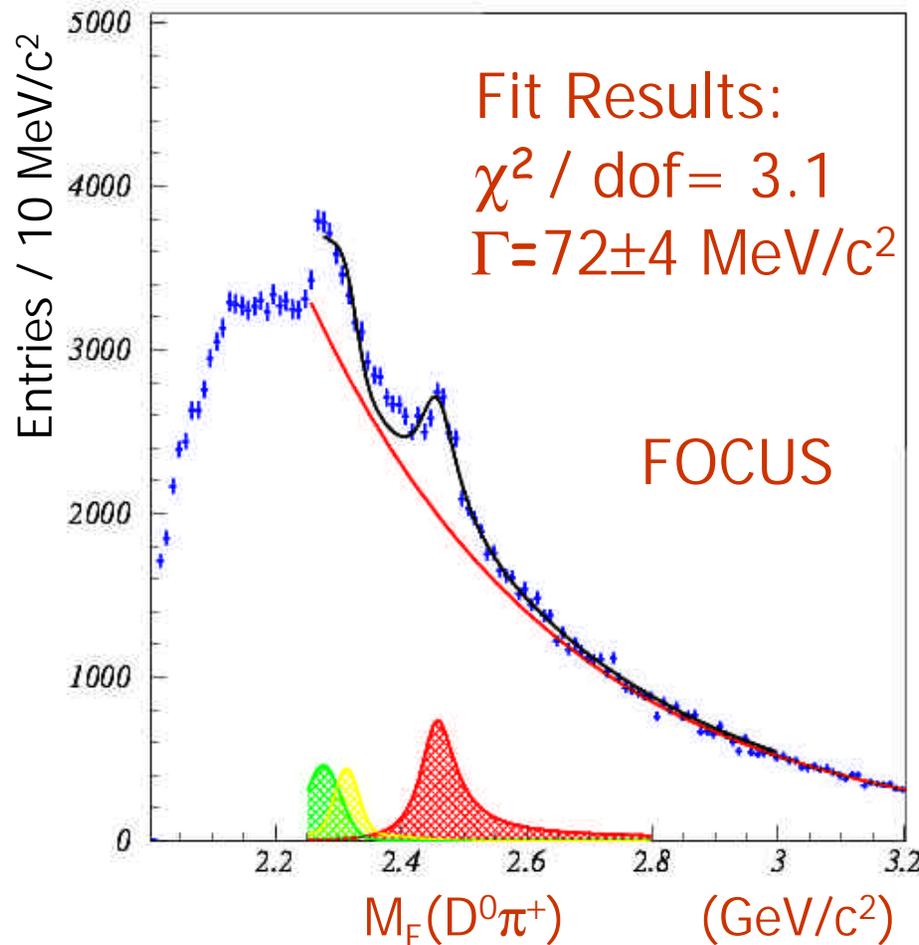
Get Feed-down Line Shapes from Monte Carlo



Beyond Signal Region all Shapes are Exponential



Fitting the $D^0\pi^+$ Mass Distribution (1)



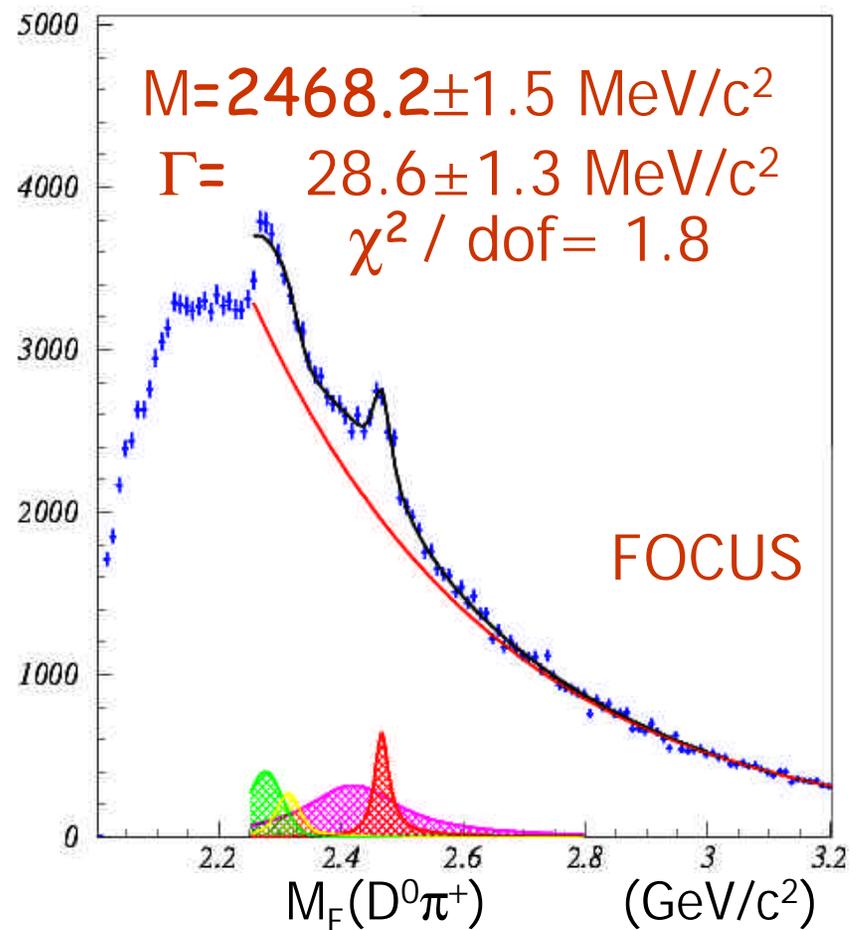
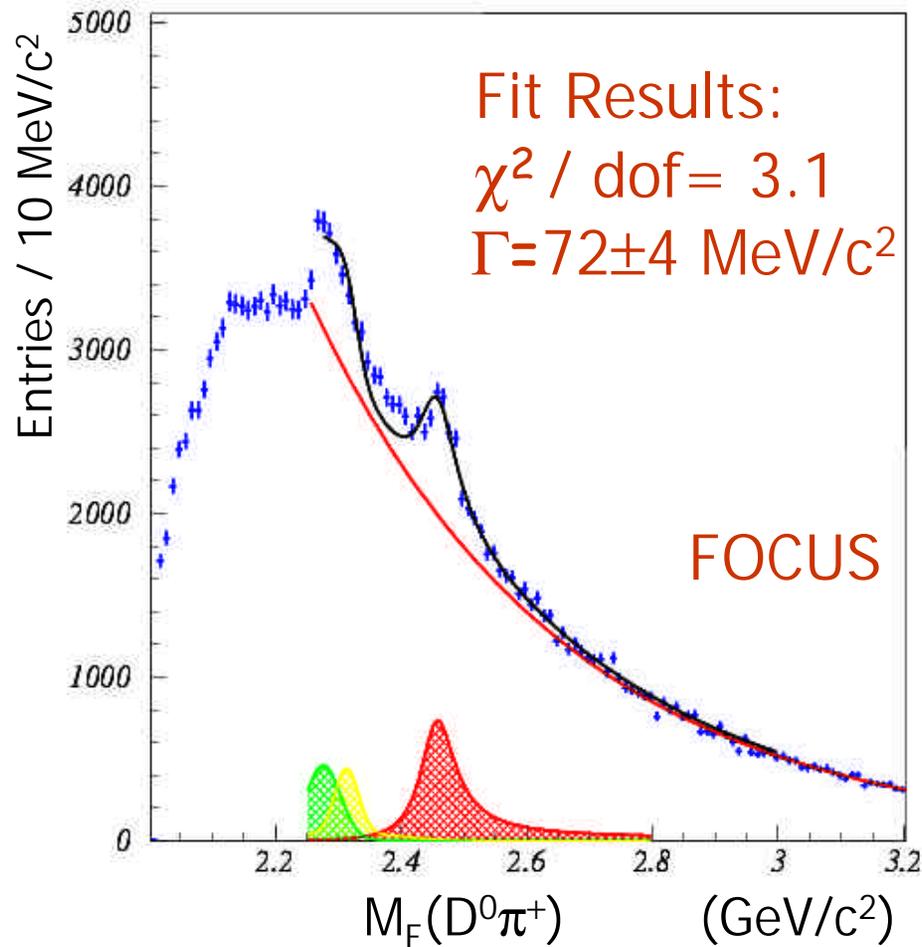
Terms in the Fit:

1. Signal: D-wave Rel. BW, convoluted with a gaussian, $\sigma = 7 \text{ MeV}/c^2$.
2. Exponential extrapolated from 2.4 – 4.5 GeV/c².
3. MC D_1 Feed-down.
4. MC D_2 Feed-down

Get horrible fit!

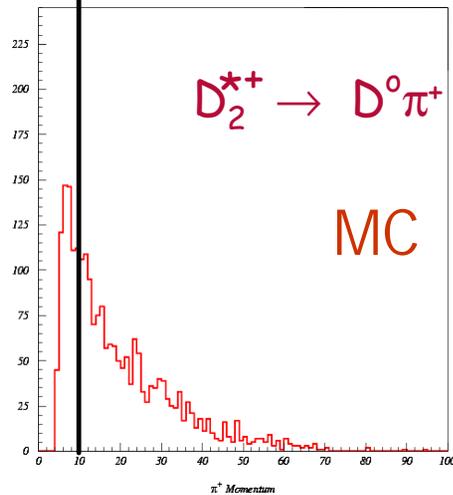
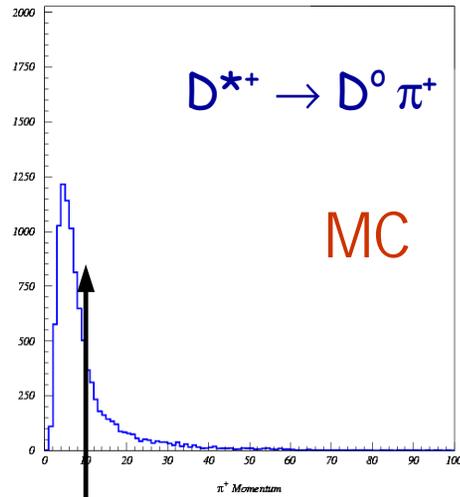
$$(\Gamma_{\text{PDG}}(D_2^{*+}) = 25 \pm 8 \text{ MeV}/c^2)$$

Fitting the $D^0\pi^+$ Mass Distribution (2)



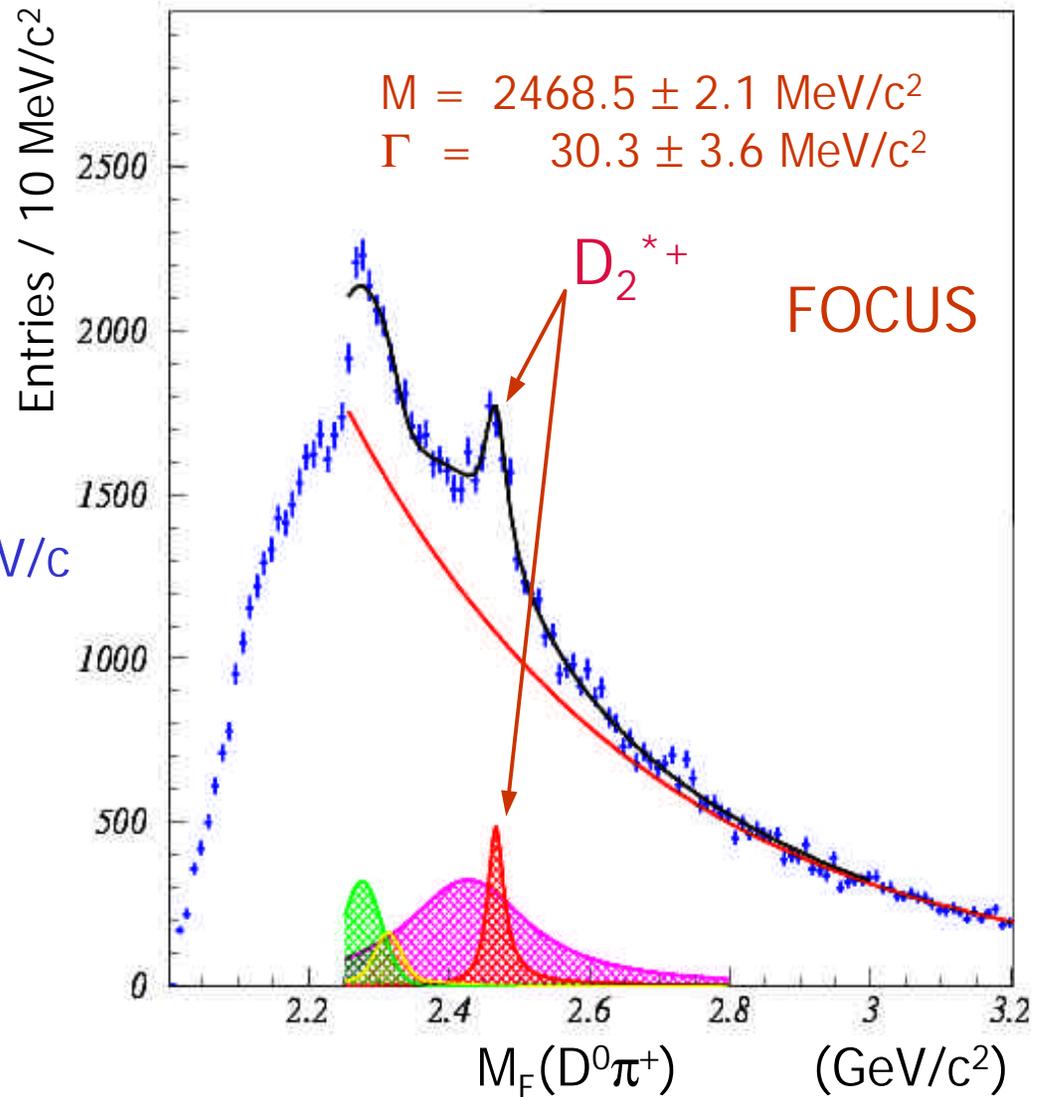
Add 5th term to the fit: S-wave Rel. BW

Reducing BG from Soft π^+ From D^{*+} Decays

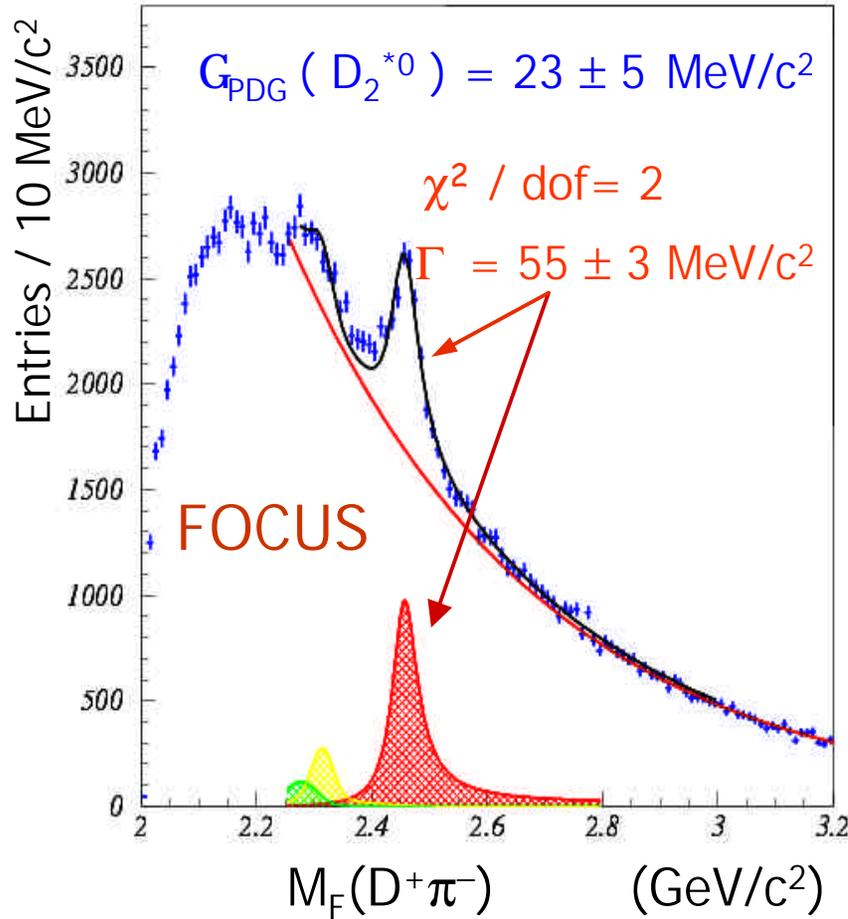


Pion momentum (GeV/c)

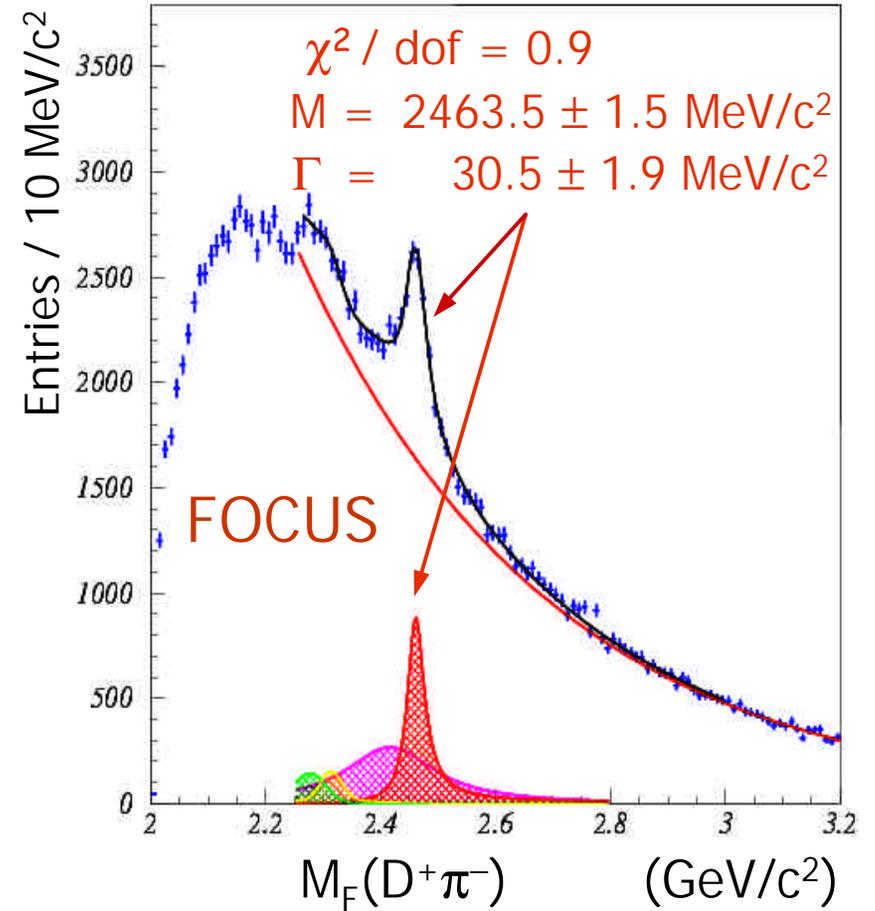
$p_\pi > 10 \text{ GeV/c}$



Fitting the $D^+\pi^-$ Mass Distribution

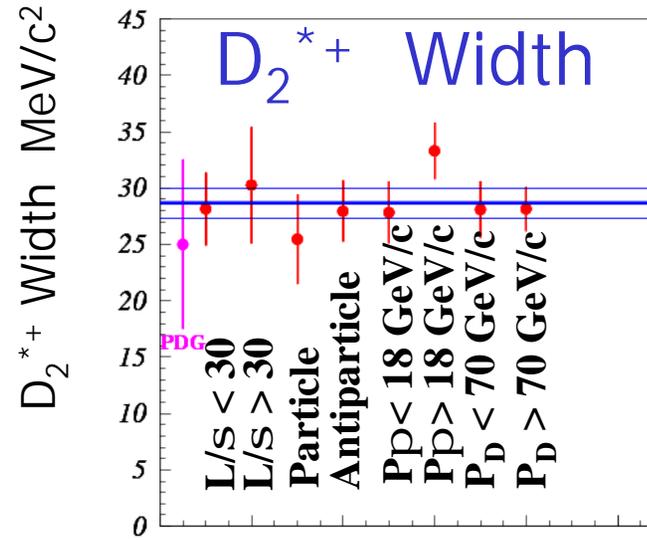
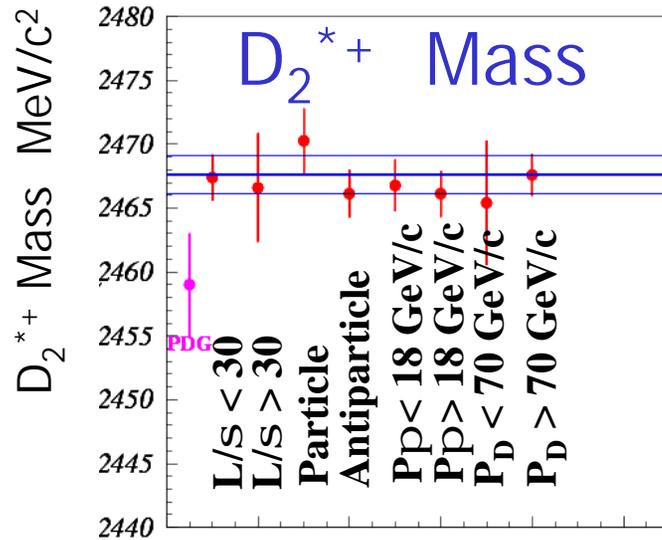


Signal + Exp + D_1 + D_2



+ S-Wave Rel. BW

D_2^* Mass and Width Systematics



Preliminary

FOCUS D_2^* Results

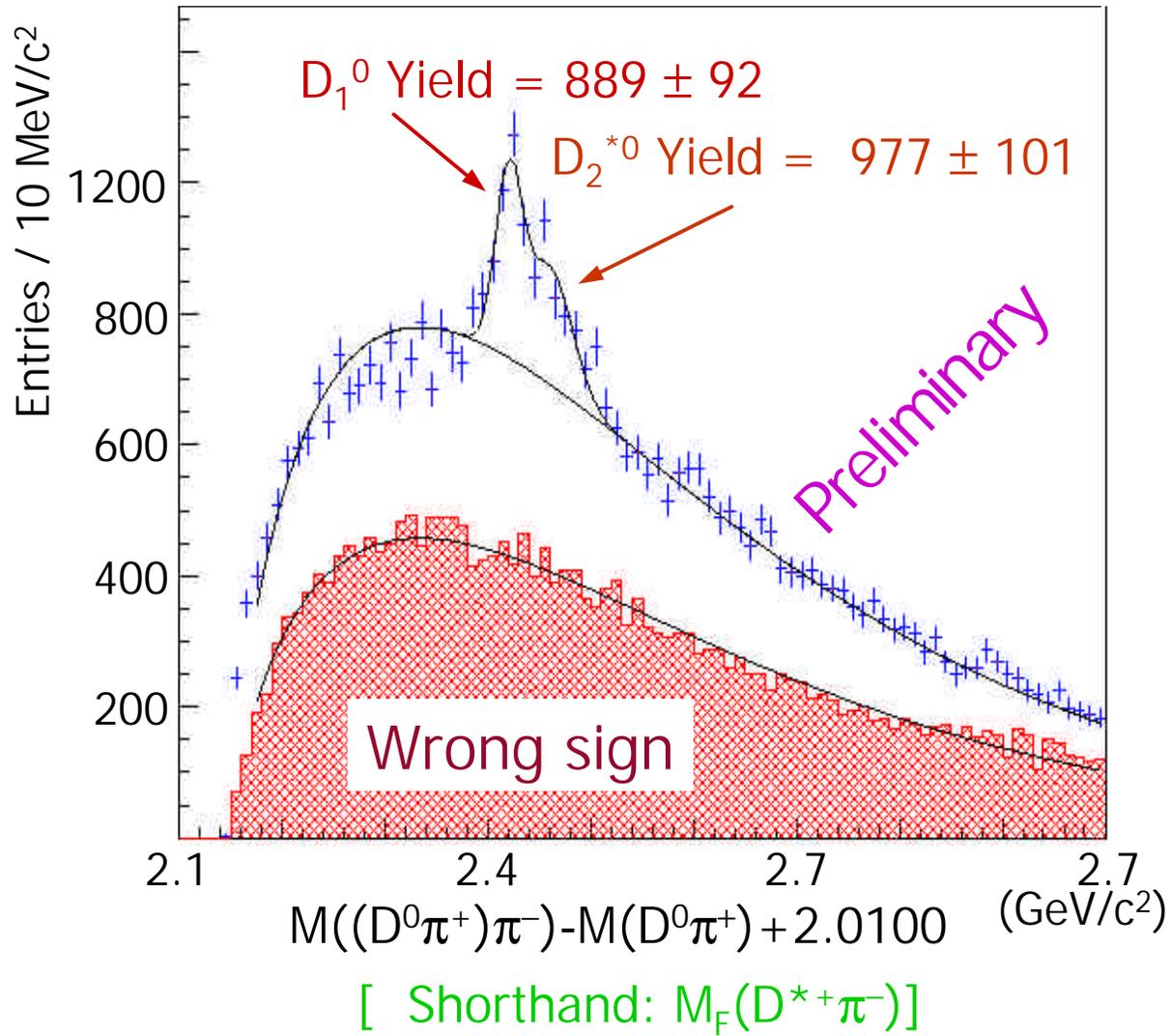
Mass (MeV/c^2)

Γ (MeV/c^2)

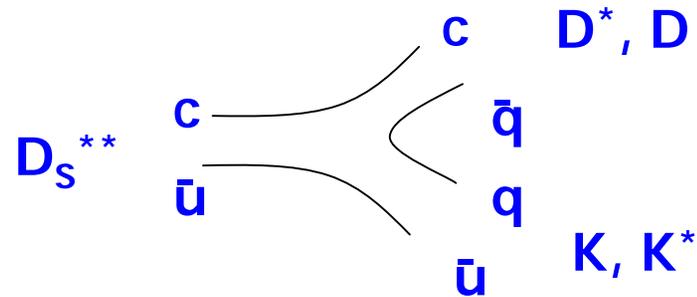
D_2^{*+}	$2468.2 \pm 1.5 \pm 1.4$	$28.6 \pm 1.3 \pm 3.8$
D_2^{*0}	$2463.5 \pm 1.5 \pm 1.5$	$30.5 \pm 1.9 \pm 3.8$

PDG 2000: $M^+ = 2459 \pm 4$, $M^0 = 2458.9 \pm 2.0$, $\Gamma^+ = 25 \pm 8$, $\Gamma^0 = 23 \pm 5 \text{ MeV}/c^2$.

$D^{*+}\pi^-$ Mass Distribution



Observation of the D_{S2}^* and D_{S1}



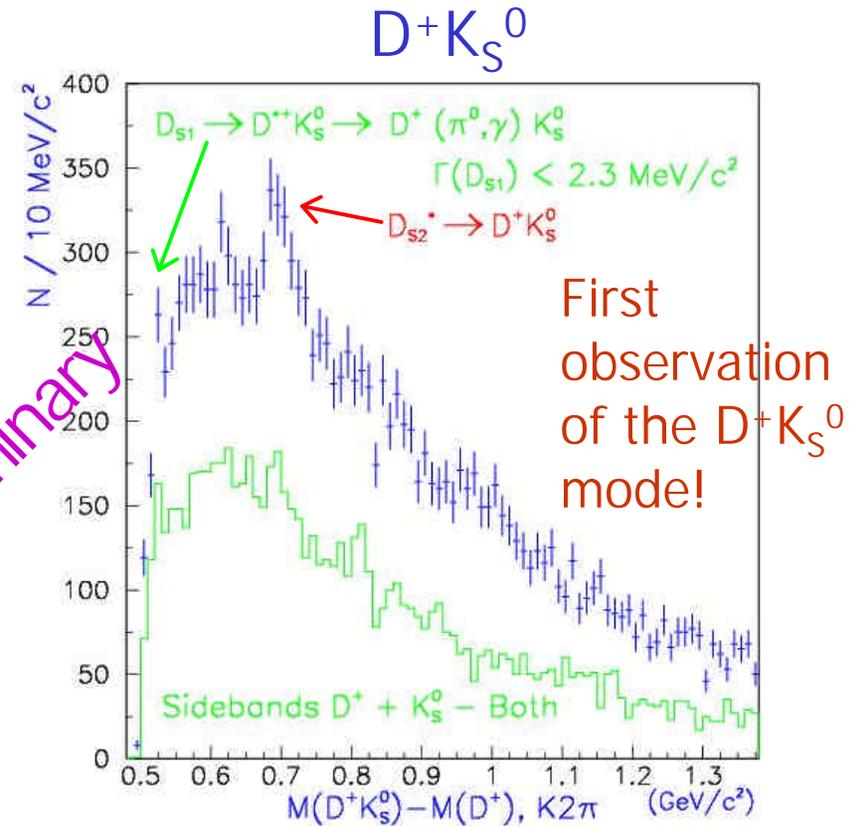
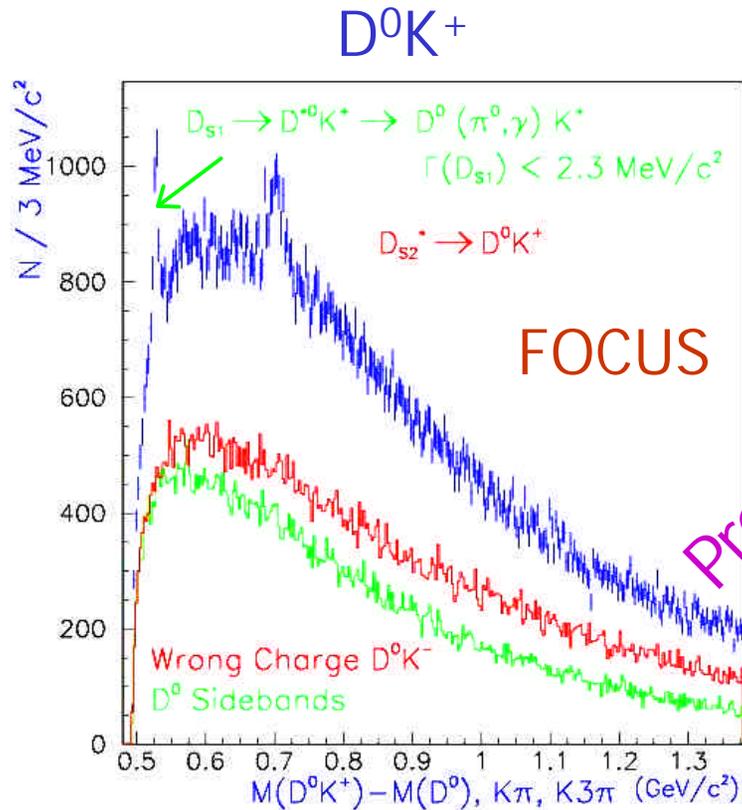
$$D_{S2}^* \rightarrow D^0 K^+ \\ \rightarrow D^+ K_S^0$$

$$D_{S1} \rightarrow D^{*+} K_S^0 \\ D^{*+} \rightarrow D^0 \pi^+$$

$$D^0 \rightarrow K^- \pi^+, \quad K^- \pi^+ \pi^+ \pi^-$$

$$D^+ \rightarrow K^- \pi^+ \pi^+$$

Observation of the D_{s2}^* at Focus

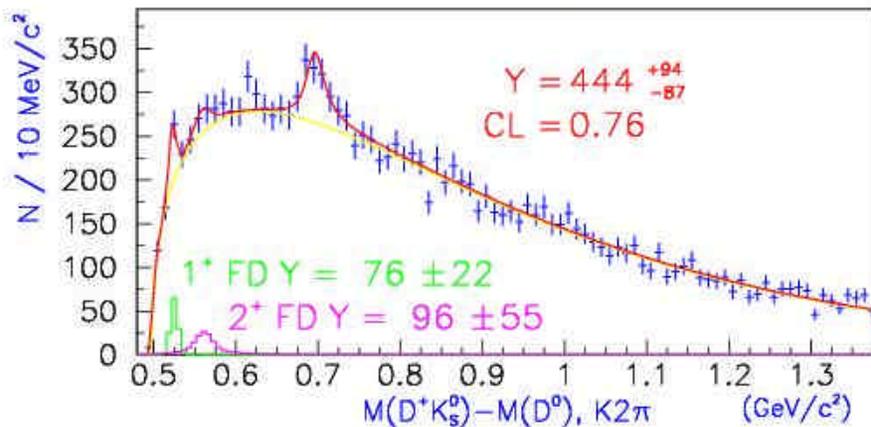
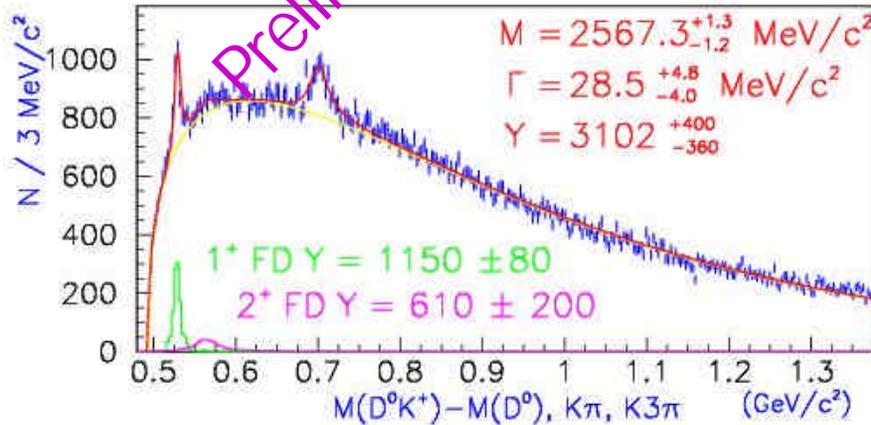


Preliminary

There are some real K_S^0 in the sideband sample.

Simultaneous Fits to D^0K^+ and $D^+K_S^0$ Spectra

Preliminary



First observation of $D^+K_S^0$ mode

Terms in the fit:

1. D_{S2} Signal: D-wave Rel. BW
2. Smooth background shape
3. MC D_{S1} feeddown shape
4. MC D_{S2} feeddown shape. Significance is not stable with cut variations!

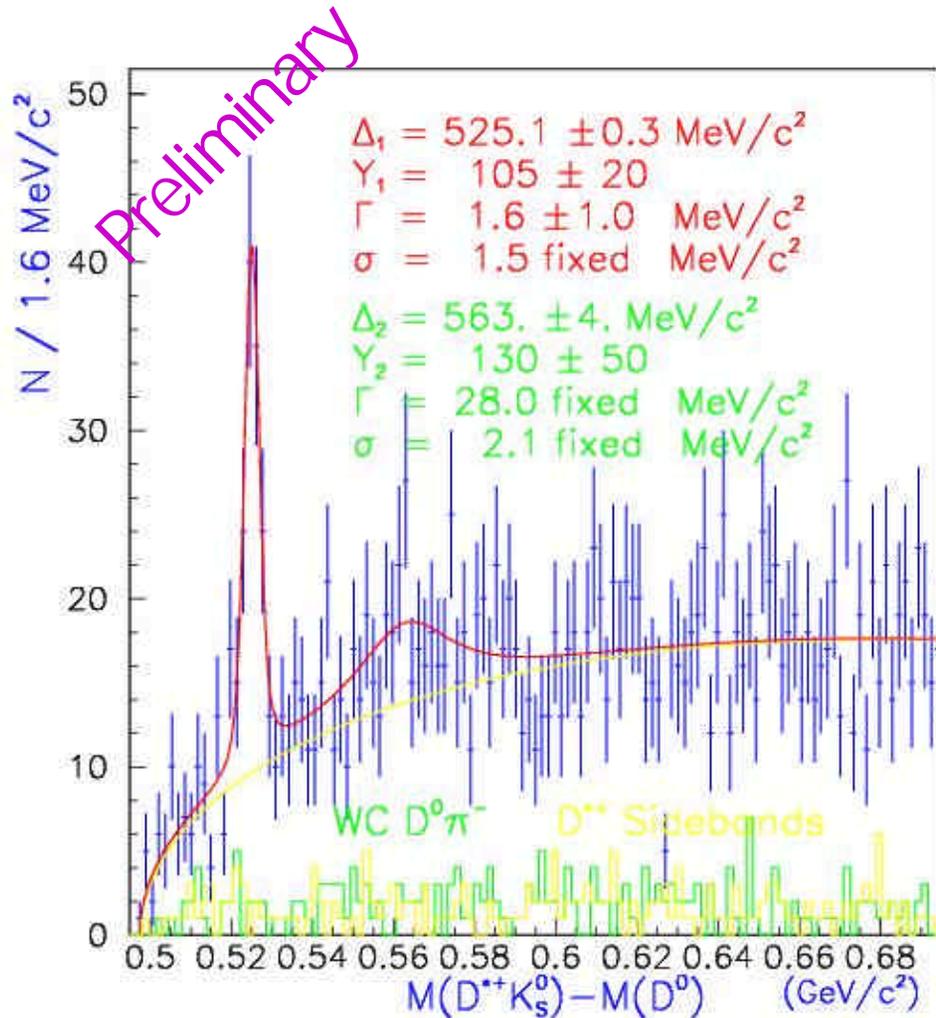
- Simultaneous: M and Γ same.
- Errors are statistical only

PDG:

$$M = 2573.5 \pm 1.7 \text{ MeV}/c^2$$

$$\Gamma = 15 \pm 5 \text{ MeV}/c^2$$

Observation of the D_{S1} at FOCUS



Terms in the fit:

1. D_{S1} Signal: Non Rel BW, convoluted with a gaussian.
2. Smooth background shape.
3. D_{S2}^* Signal: D-wave Rel BW.

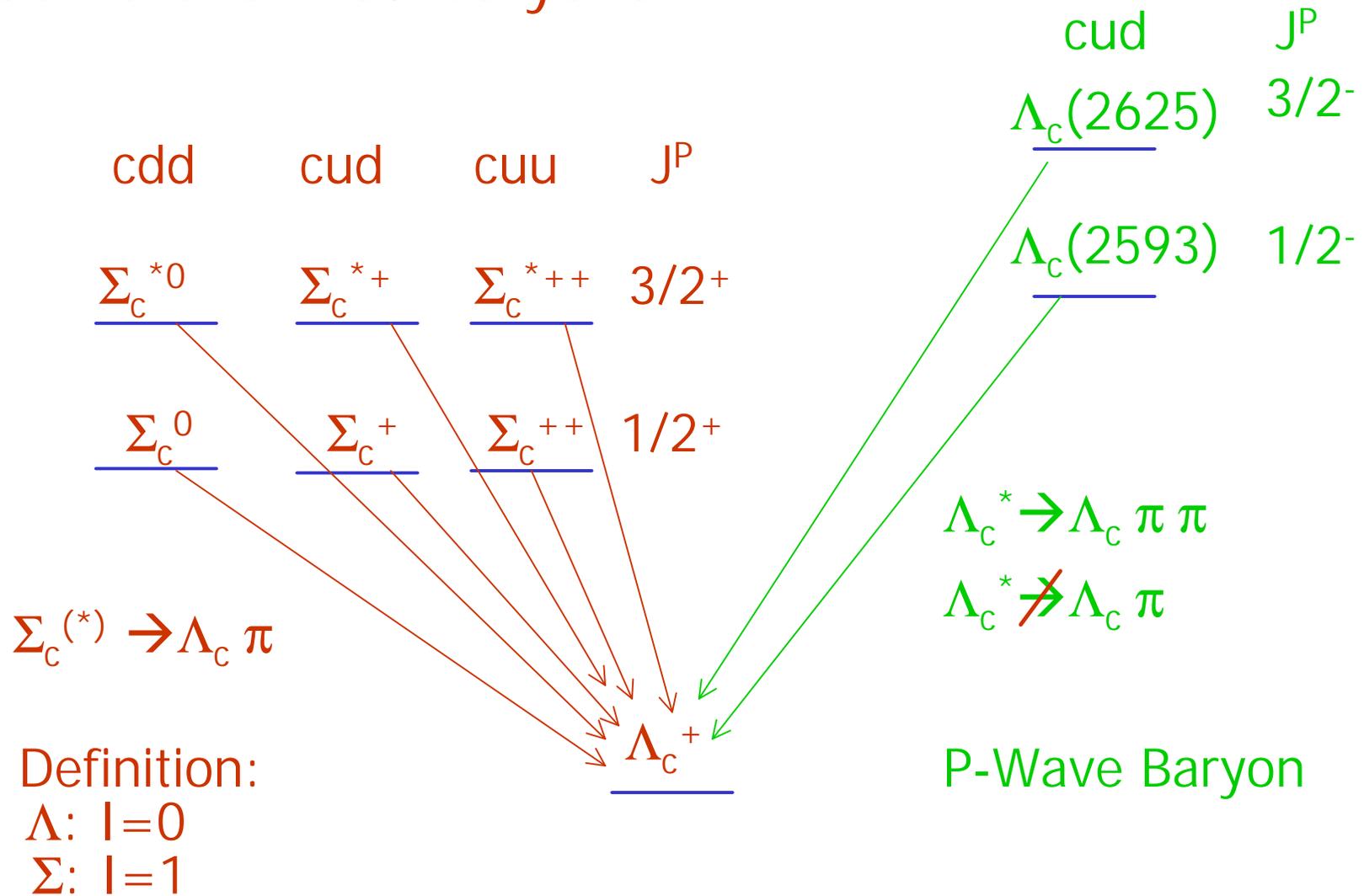
- Errors are statistical only

PDG:

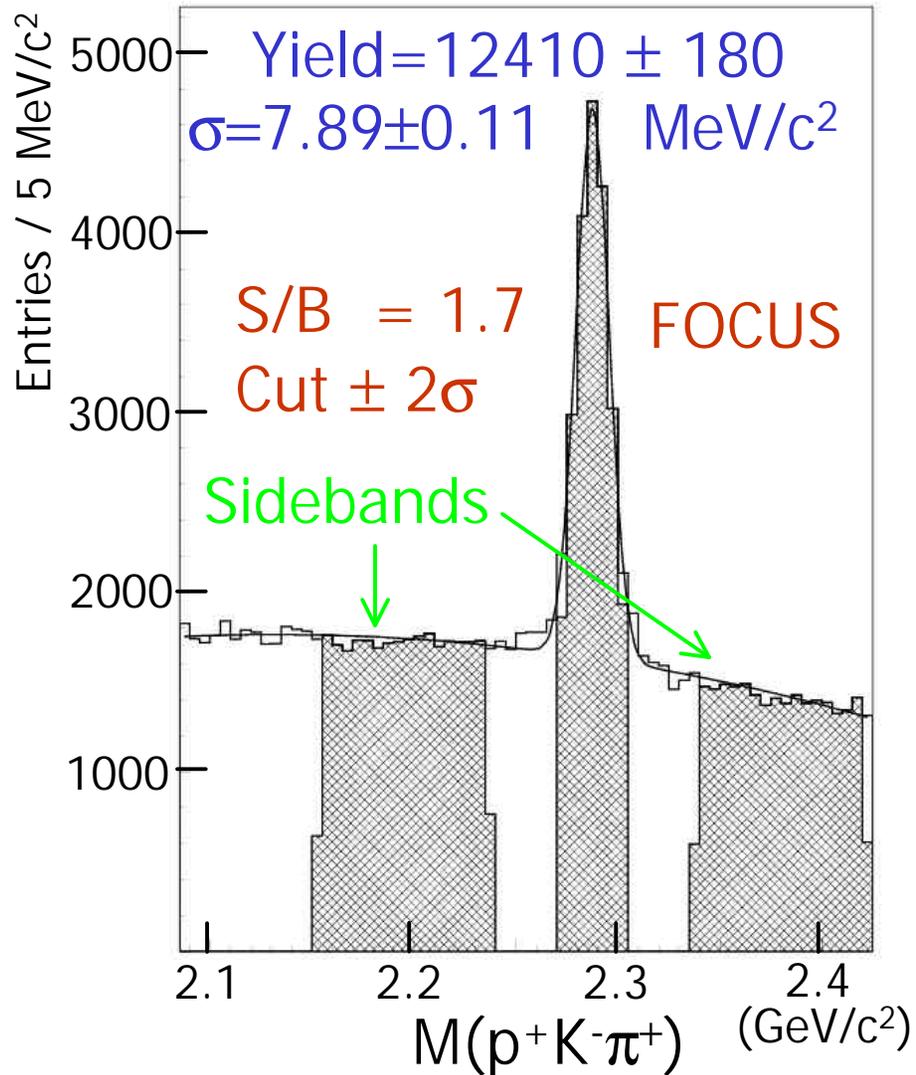
$$\Delta = 525.35 \pm 0.34 \text{ MeV}/c^2$$

$$\Gamma < 2.3 \text{ MeV}/c^2 \text{ @ } 90 \% \text{ CL.}$$

Some Charmed Baryons:

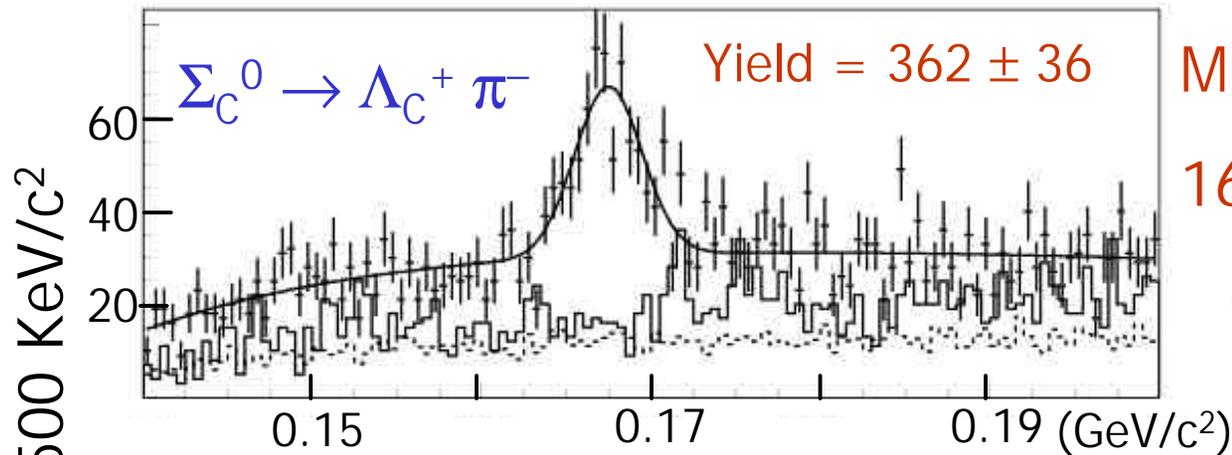


Selection of Λ_c for Σ_c^{++} and Σ_c^0 Studies

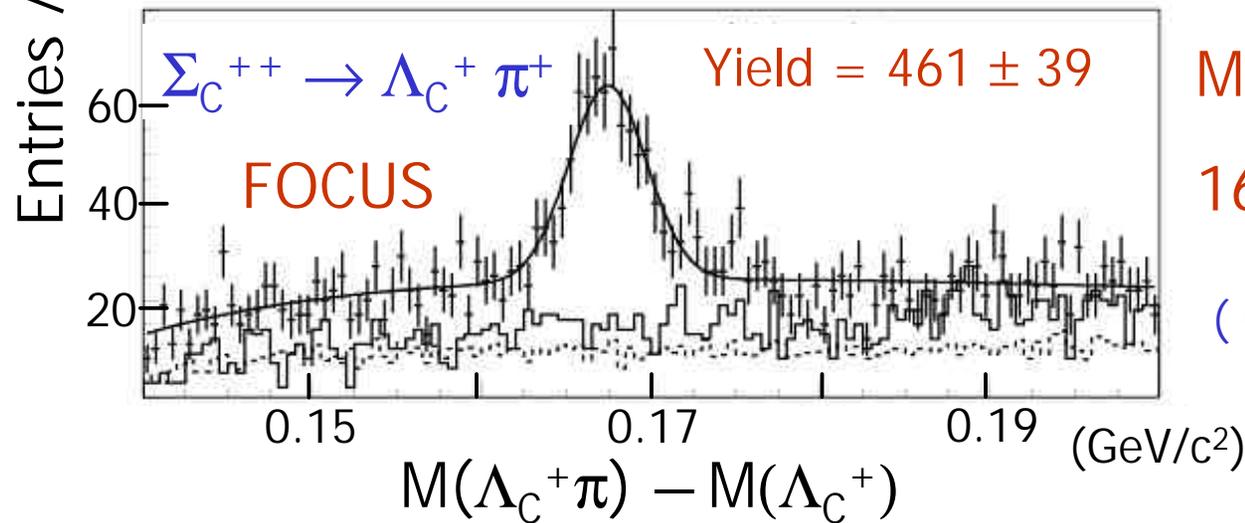


- $L/\sigma_L > 6$.
- Isolated secondary vertex.
- C affirmative Id for p and K
- C consistency for π
- For Σ_c^+ study
 - $L/\sigma > 4$, Looser C.
 - Yield = 18346 ± 248
 - S/B = 1.19

Σ_c^{++} and Σ_c^0 Masses



$M(\Sigma_c^0) - M(\Lambda_c^+) =$
 $167.38 \pm 0.21 \text{ MeV}/c^2$
 (CLEO 2.5 ICHEP 2000
 $167.2 \pm 0.1 \pm 0.2 \text{ MeV}/c^2$)



$M(\Sigma_c^{++}) - M(\Lambda_c^+) =$
 $167.35 \pm 0.19 \text{ MeV}/c^2$
 (CLEO 2.5 ICHEP 2000
 $167.4 \pm 0.1 \pm 0.2 \text{ MeV}/c^2$)

Systematic Errors

Source	Systematic Error (MeV/c ²)		
	$\Sigma_c^{++} - \Lambda_c^+$	$\Sigma_c^0 - \Lambda_c^+$	$\Sigma_c^{++} - \Sigma_c^0$
Momentum Scale	0.05	0.05	0.00
Fitting	0.02	0.06	0.04
Recon. Bias	0.04	0.04	0.00
Analysis Cuts	0.10	0.10	0.10
Total	0.12	0.13	0.11

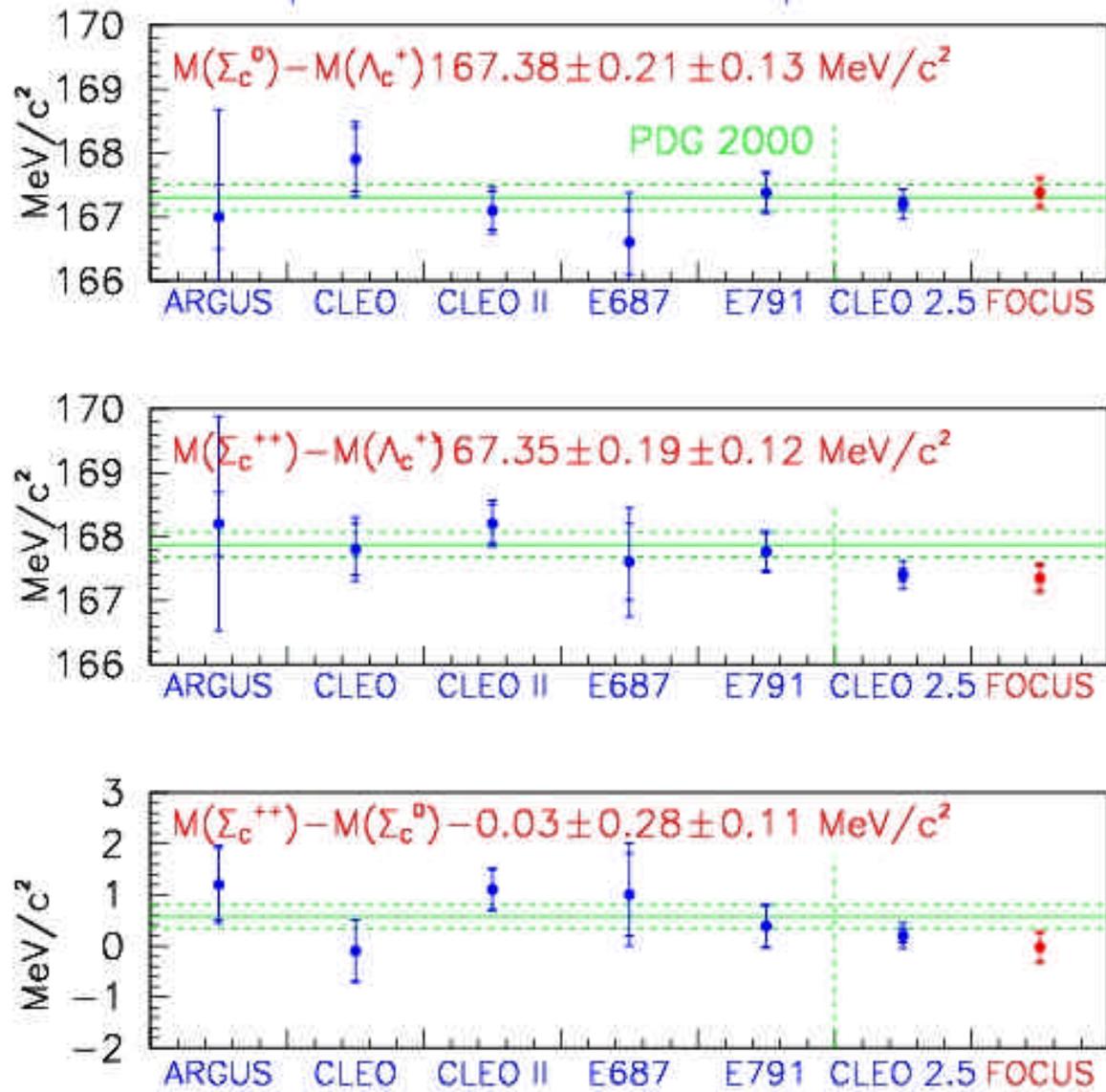
$$M(\Sigma_c^0) - M(\Lambda_c^+) = 167.38 \pm 0.21 \pm 0.13 \text{ MeV}/c^2$$

$$M(\Sigma_c^-) - M(\Lambda_c^-) = 167.35 \pm 0.19 \pm 0.12 \text{ MeV}/c^2$$

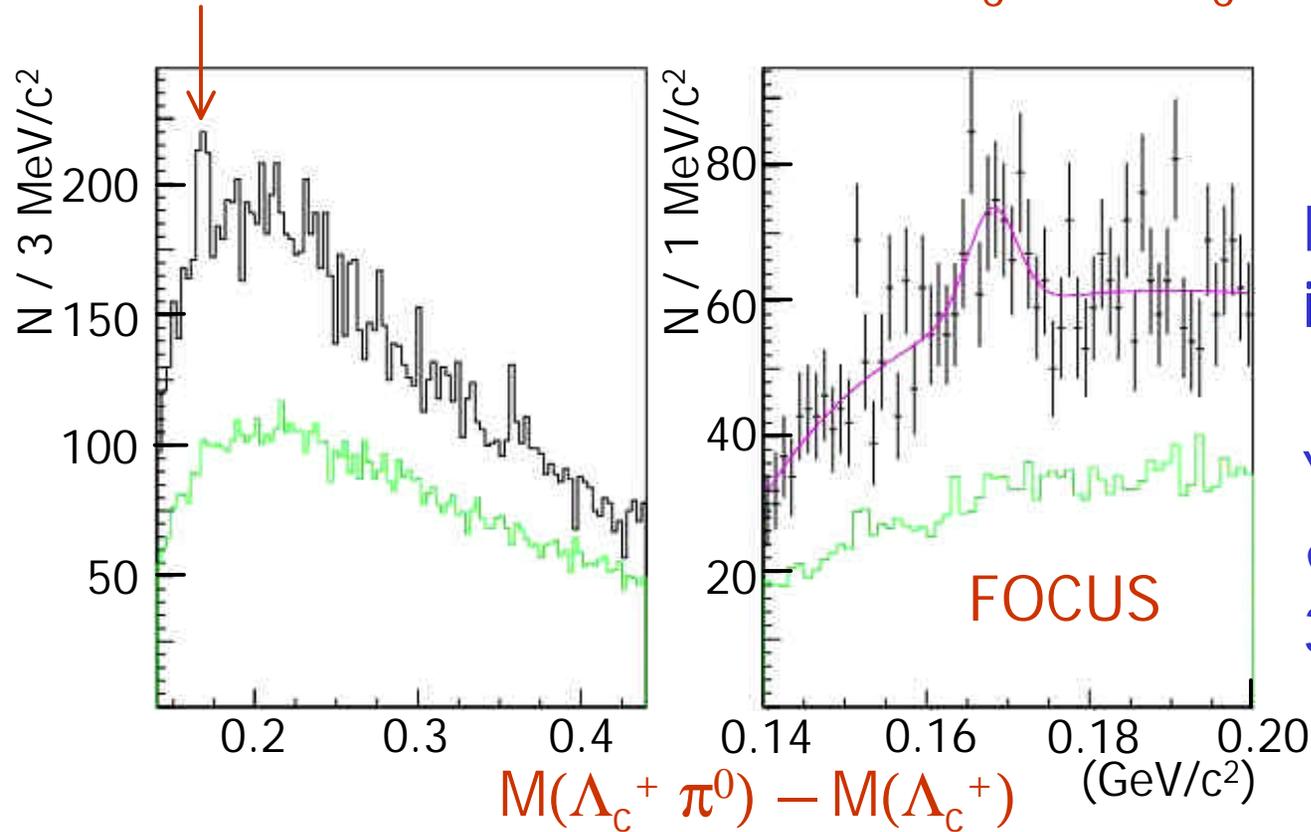
$$M(\Sigma_c^{++}) - M(\Sigma_c^0) = -0.03 \pm 0.28 \pm 0.11 \text{ MeV}/c^2$$

Phys. Lett. B488, 218-224, 2000.

Comparison with Other Experiments



Observation of $\Sigma_c^+ \rightarrow \Lambda_c^+ \pi^0$



$\pi^0 \rightarrow \gamma\gamma$
Reconstructed
in EMCAL.

Yield = 118 ± 40
 $\sigma =$
 $3.04 \pm 0.84 \text{ MeV}/c^2$

Preliminary

$$M(\Sigma_c^+) - M(\Lambda_c^+) = 168.0 \pm 1.0 \pm 0.3 \text{ MeV}/c^2$$

$$M(\Sigma_c^+) - M(\Sigma_c^0) = 0.6 \pm 1.0 \pm 0.3 \text{ MeV}/c^2$$

(CLEO hep_ex/0007041: $M(\Sigma_c^+) - M(\Lambda_c^+) = 166.4 \pm 0.2 \pm 0.3 \text{ MeV}/c^2$)

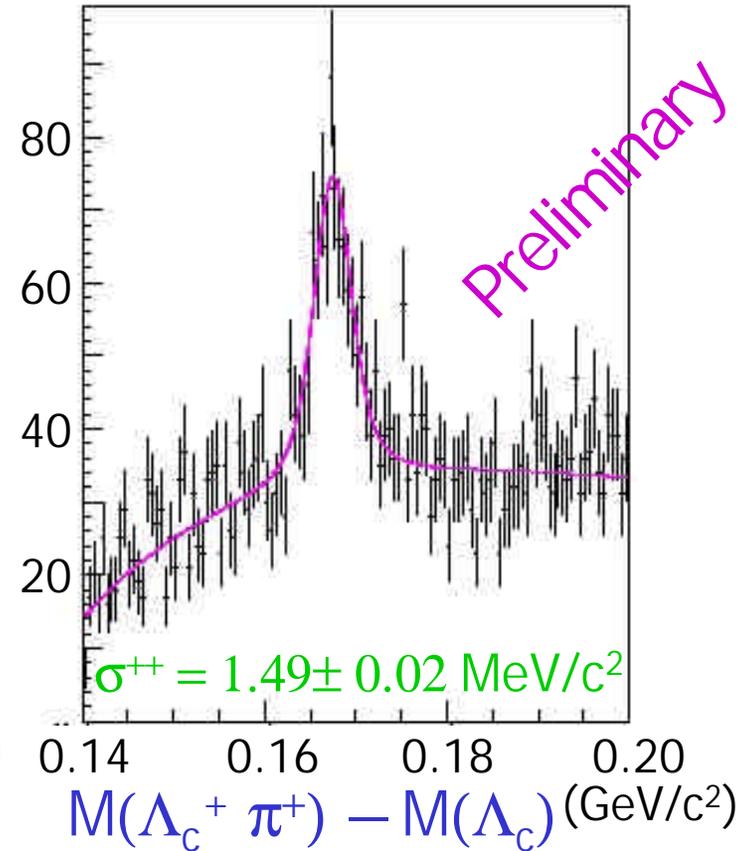
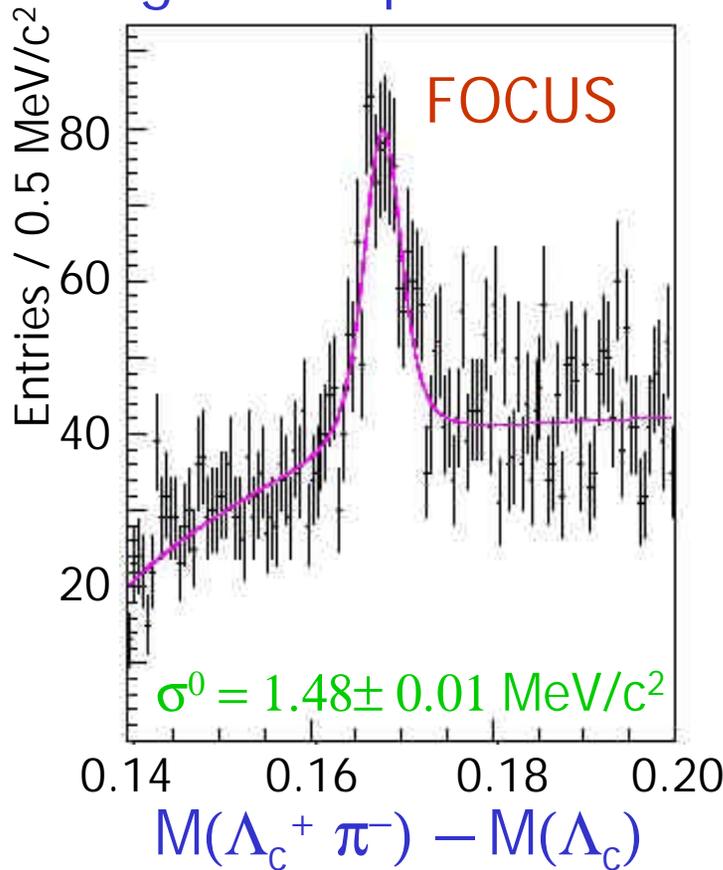
Isospin Mass Differences

Particles	Mass Difference (MeV/c ²)		
	PDG 1998	CLEO 2.5	FOCUS
N-P	1.293318 ± 0.000009		
$\Delta^0 - \Delta^{++}$	2.6 ± 0.4		Preliminary
$\Sigma^- - \Sigma^+$	8.08 ± 0.08		
$\Xi^- - \Xi^0$	6.4 ± 0.6		
$\Xi_c^0 - \Xi_c^+$	4.7 ± 0.6		
$\Sigma_c^0 - \Sigma_c^{++}$	-0.57 ± 0.23		0.03 ± 0.28 ± 0.11
$\Sigma_c^0 - \Sigma_c^+$	-1.4 ± 0.6	0.7 ± 0.5	-0.6 ± 1.0 ± 0.3

Theory has canceling contributions: quark masses, strong potential, Coulomb interaction, hyperfine (EM + QCD).

Natural Widths (MeV/c²)

Signal Shape: BW convoluted with a gaussian.



$$\Gamma(\Sigma_c^0) = 2.58 \pm 0.79^{+0.51}_{-0.55}$$

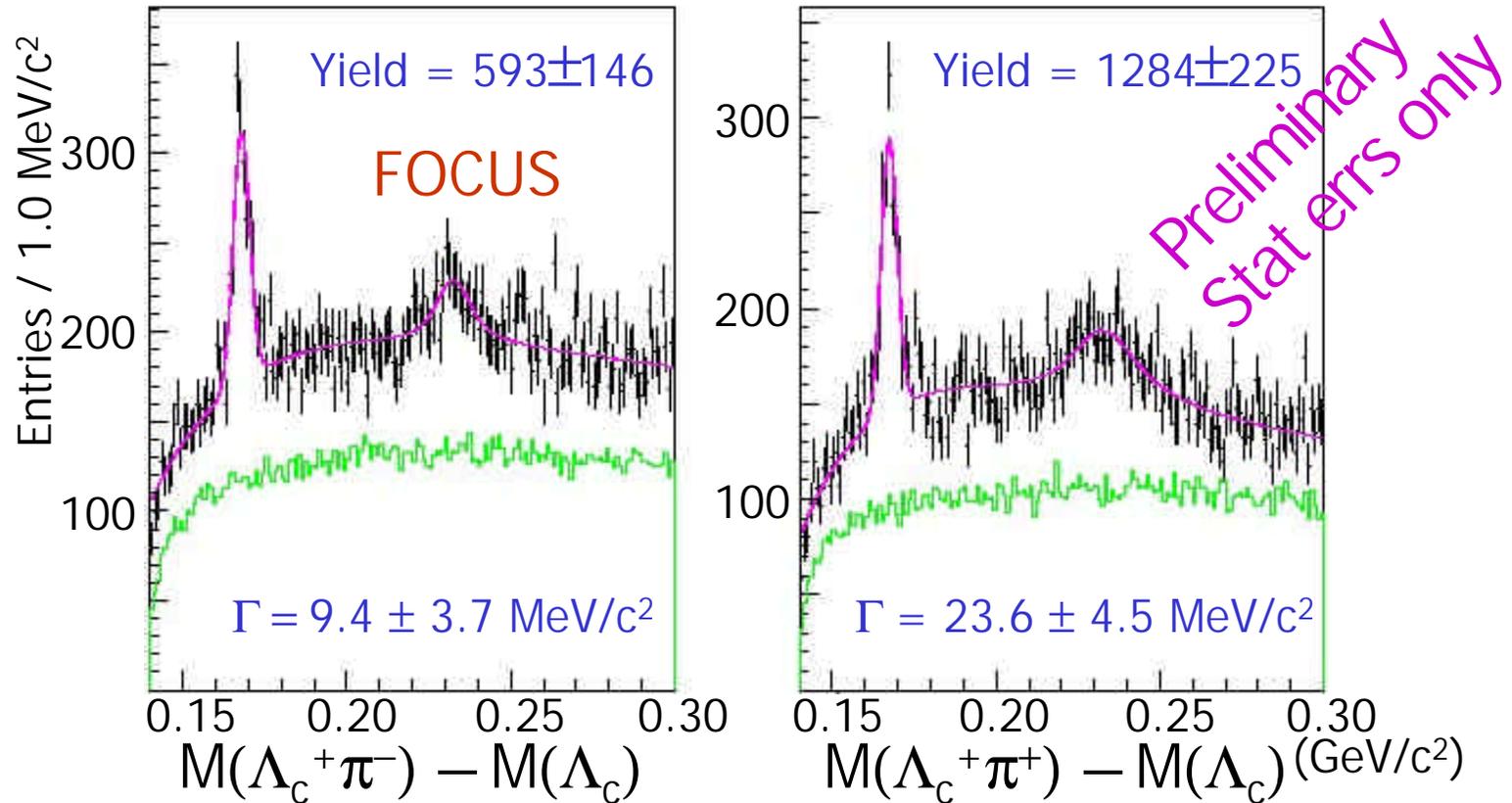
$$\Gamma(\Sigma_c^{++}) = 2.53 \pm 0.77^{+0.51}_{-0.56}$$

(CLEO 2.5 ICHEP 2000: $\Gamma^0 = 2.4 \pm 0.2 \pm 0.4$ $\Gamma^{++} = 2.5 \pm 0.2 \pm 0.4$ MeV/c²)

$\Gamma(\Sigma_c^{++})$ and $\Gamma(\Sigma_c^0)$

Theoretical Predictions		
Author ‡	Γ (MeV/c ²)	
	Σ_c^0	Σ_c^{++}
Ivanov	2.65 ± 0.19	2.85 ± 0.19
Tawfig	1.57	1.64
Huang	2.4	2.5
Pirjol	1.0 - 3.0	1.1 - 3.1
Rosner	1.32 ± 0.04	1.32 ± 0.04
‡ References at end of talk.		
Focus Preliminary Results		
	$2.58 \pm 0.79^{+0.51}_{-0.55}$	$2.53 \pm 0.77^{+0.51}_{-0.56}$

Observation of Σ_c^{*++} and Σ_c^{*0}

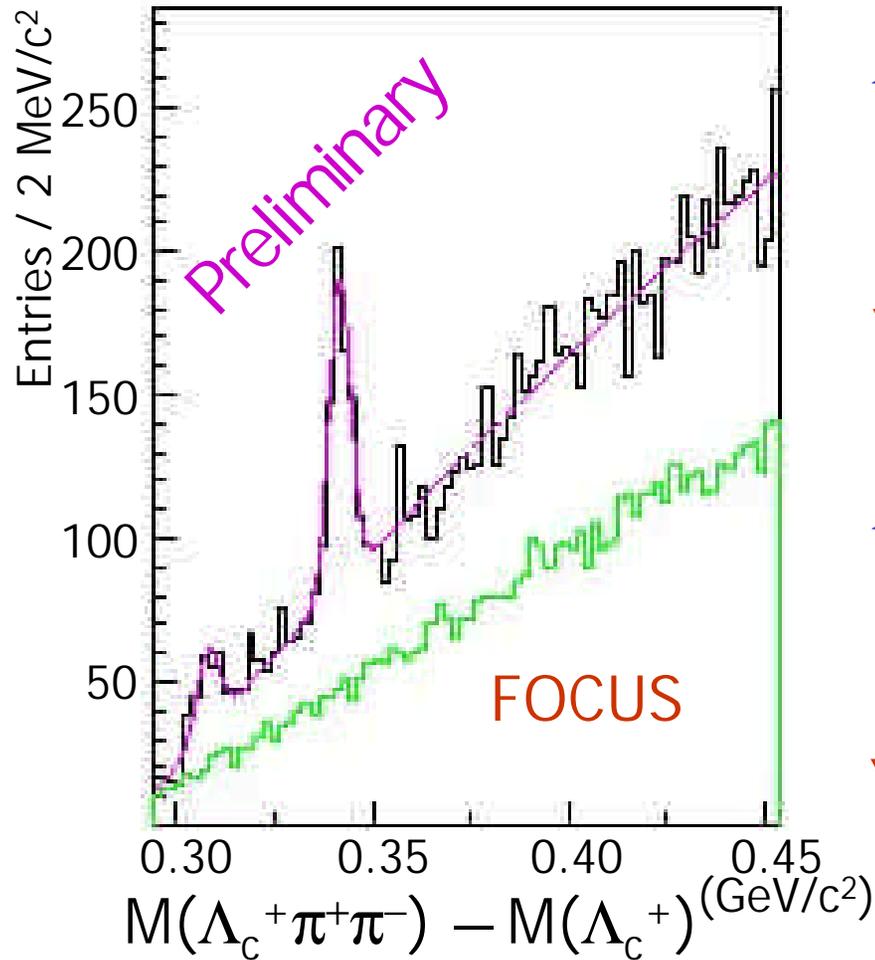


$$\Delta M(\Sigma_c^0) = 232.7 \pm 1.2 \text{ MeV}/c^2 \quad \Delta M(\Sigma_c^{*++}) = 234.2 \pm 1.5 \text{ MeV}/c^2$$

$$M(\Sigma_c^{*0}) - M(\Sigma_c^{*++}) = -1.5 \pm 1.9 \text{ MeV}/c^2$$

(CLEO II: $\Delta M^0 = 232.6 \pm 1.0 \pm 0.8$ $\Gamma^0 = 13.0 \pm 3.7 \pm 4.0$ $\Delta M^{*++} = 234.5 \pm 1.1 \pm 0.8$ $\Gamma^{*++} = 17.9 \pm 3.8 \pm 4.0$)

Observation of Excited Λ_c States



$\Lambda_c(2625)$:

$$\Delta M = 341.6 \pm 0.3 \text{ MeV}/c^2$$

(PDG 2000: 341.7 ± 0.6)

$$\text{Yield} = 371 \pm 32$$

$\Lambda_c(2593)$:

$$\Delta M = 308.1 \pm 0.7 \text{ MeV}/c^2$$

(PDG 2000: 308.9 ± 0.6)

$$\text{Yield} = 100 \pm 20$$

Errors are Stat only.

Summary and Conclusions

- Preliminary masses and widths in D^{**} and D_S^{**} sectors.
- First observation of $D_{S2}^* \rightarrow D^+ K_S^0$.
- Confronting a new level of systematics in the D^{**} sector
 - We require something like the expected broad state to fit the mass difference spectrum successfully.
- Measurements of Σ_C^{++} and Σ_C^0 Masses and Widths
 - **Published:** $M(\Sigma_C^{++}) - M(\Sigma_C^0) = -0.03 \pm 0.28 \pm 0.11 \text{ MeV}/c^2$
- Confirm Σ_C^+ , Σ_C^{*++} , Σ_C^{*0} previously seen only by CLEO II.
- A good start on Λ_C^*

References for Theory on Page 30

1. M.A. Ivanov et al., Phys. Lett. B442, 435 (1998).
2. M.A. Ivanov et al., Phys. Rev. D60, 094002 (1999).
3. S. Tawfig et al., Phys. Rev. D58, 054010 (1998).
4. M.-Q. Huang et al., Phys. Rev. D52, 3986 (1995).
5. D. Pirol and T.-M. Yan, Phys. Rev D56, 5483 (1997).
6. J.L. Rosner, Phys. Rev. D52, 6461 (1995).